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EXPERIMENTAL TEST FACILITY FOR EVALUATION OF CONTROLS
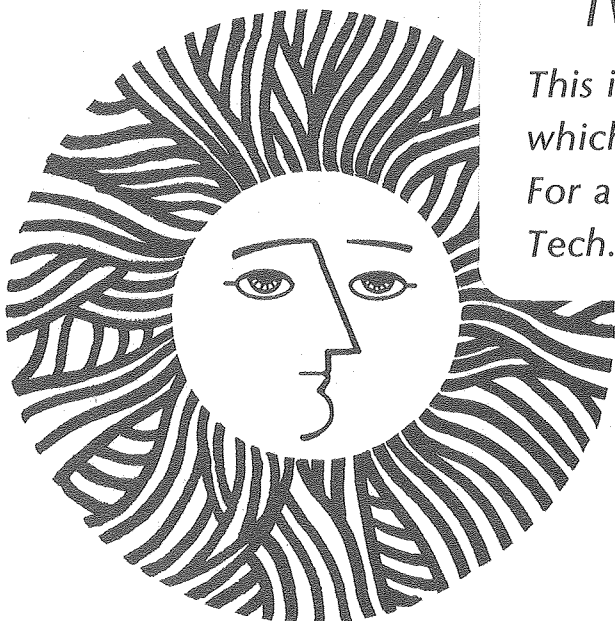AND CONTROL STRATEGIES

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EXPERIMENTAL TEST FACILITY FOR EVALUATION OF CONTROLS AND CONTROL STRATEGIES[*].

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ABSTRACT

An experimental test facility has been constructed to evaluate the operation and performance of controls for active hydronic solar energy systems. The experimental system serves to test the relative performance of different controllers and alternative control algorithms for a variety of input meteorological conditions and output load demands.

The experimental system consists of a collector loop heat input simulator, a storage tank, a load loop air channel with fan coil, an auxiliary heat source, and associated pumps and valves. The heat input simulator, the pseudo-collector, consists of a boiler with a controlled mixing valve that allows precise adjustment of the heat input from the "collectors" based on predictions of a collector loop model using solar and weather data. An automated air flow channel has been constructed to simulate the building return airflow across the heating coil in the furnace ductwork for a residential system. A single zone building load model is used to predict building energy requirements and to simulate the demand thermostat. Only the apparent temperature of the collector and the demand thermostat condition are simulated, enabling control strategy and equipment comparisons based on identical load conditions.

The test facility is well instrumented with thermocouples and turbine flow meters. Data acquisition is accomplished using a one hundred channel DORIC data logger. Data acquisition, experiment control, and the load and pseudo-collector models are under control of a HP 9825A microcomputer using flexible disks for data and program storage.

Initial experiments have been done using an LBL-developed PROM based controller to control all functions of the solar system. Preliminary energy balance tests, reported previously, indicate that the overall heat balance for the experiments is within 5% of the total heat input. The criterion for evaluation of performance of a controller and/or control strategy is the amount of auxiliary energy required to meet a given load demand. The test facility is now operational and initial test results over many hours, with simulated collector heat input and simulated building load under microcomputer control, will be reported.

INTRODUCTION

The test facility is used to experimentally evaluate the relative performance of different solar heating control strategies for a variety of input meteorological conditions and heating load demands. To allow repeated runs under identical external conditions and to make meaningful comparisons between alternative control strategies, the solar energy input to the system and the building energy load are simulated. In this paper we shall describe the test facility and the methodology of the solar heat input and building load simulators. Initial test results are also presented.

EXPERIMENTAL TEST FACILITY

The experimental solar energy system consists of a collector loop with a solar heat input simulator, a 3000 gallon storage tank, a load loop air channel with fan coil, an auxiliary heat source, and associated pumps and valves. A schematic of the system is shown in Figure 1. The system is sized to represent a hydronic solar heating system in a typical residence. The operation of the solar energy system is controlled by a PROM based controller developed at LBL that uses thermostat signals and temperature sensor comparisons to address a truth table containing the control algorithm used to control system actuators. This controller

has been described previously[1,2].

INSTRUMENTATION AND DATA ANALYSIS SYSTEM.

The test facility is well instrumented with thermocouples and tur-
bine flow meters. Data acquisition is accomplished using a 100 channel
DORIC data logger. Data acquisition, experiment control, and the load
and pseudo-collector simulations are under control of a HP 9825A micro-
computer using flexible disk for data and program storage. Software
requirements for data acquisition, adjustment of the load and pseudo-
collector simulators, and intermediate data analysis are extensive,
exceeding the limits of the computer memory. Therefore, the software
has been rewritten in an overlay mode to greatly extend the computer
capability. Segments containing the main program, subroutines for
operation of the datalogger and output devices, experiment initializa-
tion, data analysis and control procedures are now stored on different
files and are loaded into memory from the disk as they are required.
Auxiliary gas consumption for back-up heat, and parasitic power require-
ments for the pumps and fans, are now measured electronically. The
facility instrumentation is shown in Figure 2.

SOLAR INPUT SIMULATOR (PSEUDO-COLLECTOR)

A schematic of the facility collector loop is shown in Figure 3.
The solar input simulator, the pseudo-collector, is a boiler with a con-
trolled mixing valve that allows adjustment of the input-output tempera-
ture difference. The high- and low-fire gas burners of the boiler, as
well as the position of the three way mixing valve, are all controlled

by the HP-9825A. Values of solar insolation, ambient temperature, the boiler inlet temperature and flow rate, along with typical collector parameters, are used to calculate the expected inlet-outlet temperature difference using the Hottel-Whillier-Bliss steady state model[3]. Initial experiments have been run using a simple increasing and decreasing insolation pattern. Work is presently underway to generate insolation values incident on the collector array using typical meteorological year, TMY, data tapes prepared for SERI by Science Applications, Inc.

Under no-flow conditions in the collector loop, the value of the collector sensor, TS-4, is set to the calculated collector stagnation temperature through an output device. When the collector loop pump is on, the collector output temperature is calculated from the collector model, and the boiler output is adjusted accordingly. The apparent collector temperature and boiler control are updated every 60 seconds.

The PROM system controller turns on the collector loop pump, P1, when the apparent collector temperature reaches the "on" set point, given by the storage tank temperature plus a temperature differential, ΔT_{on} of 11 $^{\circ}$C. The pump is turned off if the collector temperature falls below the "off" temperature, given by the storage tank temperature plus a temperature differential, ΔT_{off} of 2 $^{\circ}$C.

Figure 4 shows the inlet temperature and the calculated and observed collector outlet temperature over a four hour period of increasing and decreasing insolation. If the collector outlet temperature under flow conditions is less than the off temperature and the collector stagnation temperature is greater than the on temperature, then the collector loop pump will cycle on and off and the collector

temperature will cycle between the "on" and "off" temperatures. Such cycling is typical of solar collector systems. The steady state collector model does not adequately describe this cycling and work is underway to implement a dynamic collector model for the solar input simulator.

LOAD SIMULATOR

The load simulator is an air channel which simulates a building's heating system consisting of a return air duct, fan and heating and cooling coils. The inlet air temperature is adjusted by an electric resistance heater and an air conditioner under the control of the HP-9825A. A schematic of the building load loop and air channel are shown in Figure 5.

The building heating requirements to be satisfied by the solar energy system are modeled in the microcomputer. A simple thermostat model is used to control the heat delivery system. As determined by McBride[4] in experimental studies, the heat delivery system is on for a fixed interval of about 5 minutes. The energy delivered to the load by the heating coil is measured and compared with the building load to determine how often heat must be supplied and whether auxiliary energy is required. Initial experiments have been run using a building effective heat loss coefficient, $UA = 500$ W/$^{\circ}$C and a typical ambient temperature varying between $20\ ^{\circ}$C and $0\ ^{\circ}$C. Work is presently under way to calculate hourly building loads using a TRNSYS compatible residential building load model[5] with recommended building parameters for typical residences in four representative cities.

INITIAL RESULTS

Initial experiments have been run on the test facility to determine the accuracy of energy balance measurements for the system. The building load and collector array size represent a typical residence in Madison, Wisconsin. Energy balances are performed during the experiment by: 1) determining the energy delivered by the pseudo-collector; 2) determining the energy stored at the beginning and end of a period; 3) determining the amount of energy delivered to the load; and 4) estimating losses from storage and piping.

Collector Loop Energy Balance.

Preliminary energy balance experiments were run with simulated solar heat input from the pseudo-collector, with the apparent collector temperature determined by the HP-9825A, and with the operation of the collector and load loop determined by the LBL electronic controller.

Energy supplied by the pseudo-collector was calculated at 60 second intervals and the amount of energy in the storage tank was calculated at 30 minute intervals as the apparent solar insolation was increased from zero to a maximum of 950 W/m^2 and then back to zero. The duration of each experiment was 4 hours.

An energy balance summary for two 4 hour experiments and for a 22 hour total of successive experiments is shown in TABLE 1. The change in storage tank energy, $\Delta Q_{storage}$, is calculated from measurements of the storage tank temperatures. Heat input from the pseudo-collector boiler is calculated using the measured flow rate and the temperature difference between inlet and outlet. Q2, the total heat supplied to the fluid

Time period	4 hrs	4 hrs	22 hrs
Heat Input			
Q2	131.9 MJ	128.6 MJ	705.2 MJ
Q4	128.6 MJ	126.1 MJ	692.3 MJ
$\Delta Q_{storage}$	113.0 MJ	118.5 MJ	663.9 MJ
Estimated Piping Losses			
Q2 –Q4	3.3 MJ	2.5 MJ	12.8 MJ
Q_{piping}	3.7 MJ	4.9 MJ	25.2 MJ
Net Energy Balance			
$\Delta Q_{storage}$	113.0 MJ	118.5 MJ	663.9 MJ
$+ \, Q_{piping}$	3.7 MJ	4.9 MJ	25.2 MJ
$+ \, Q_{loss}$	4.6 MJ	5.6 MJ	28.4 MJ
$- \, Q2$	-131.9 MJ	-128.6 MJ	-705.2 MJ
Net Balance	-10.6 MJ	-0.4 MJ	12.3 MJ
	(-9.0%)	(0.3%)	(1.7%)

TABLE 1. Collector Loop Energy Balance Summary

stream, is calculated using thermocouples just before and after the boiler. Q4, the heat supplied to storage, is calculated using thermo- couples before the boiler and at the storage return and is slightly smaller because of piping losses.

Estimates are made for heat losses from the system piping and from the storage tank, which contains 11,400 kg of water. Previous experi- ments indicate that the heat loss coefficient should be approximately 25 W/^{o}C for the collector loop piping and 24.6 W/^{o}C for the storage tank.. Estimated piping energy losses are indicated in Table 1 and compared with the difference between Q2 and Q4 which represents about one half the estimated loss, as it accounts only for the return side of the col- lector loop. Additional losses are found on the supply side.

The net energy balance is calculated by subtracting the energy

input from the change in energy storage and the estimated losses. The energy input during each four hour period was reproducible as shown in Table 1. The energy balance over a single four hour measurement period is not precise, primarily because of uncertainty in the storage tank energy measurements. Even though the storage tank energy change is calculated from the weighted average of 6 thermocouples, errors of the order of $\pm$ 10 MJ are produced as the stratification in the storage tank changes. However, over a long experimental run of 22 hours, the energy balance is quite acceptable.

Load Loop Energy Balance.

Preliminary energy balance experiments were run with heat delivered from the storage tank to the heating coil located in the air duct. Power discharged in the heating coil, Q_H, was measured every thirty seconds using a differential thermocouple measured across the coil and the load loop flow measurement, FL2. Power delivered to the load was typically 12 kW. The load loop experiment summarized in Table 2 was run for a period of 18 hours, with the building load calculated for a constant outdoor temperature of 0 ^{o}C and a building loss coefficient of 500 W/^{o}C.

The overall energy balance for the 18 hour run is quite good when estimated losses from storage, from piping, and across the heating coil are compared with the changes in the stored energy.

TESTING PLANS

Comparison tests of alternative control strategies are now begin-

Time Period   18 hrs

Storage Tank Energy Balance

$\Delta Q_{storage}$		-561.4 MJ
ΔQ_{loss}		21.8 MJ
Piping losses (estimated)		24.3 MJ
Net delivered to load		-515.3 MJ
Measured Heat To Load	Q_H	-536.7 MJ
Net Energy Balance		-21.4 MJ (4%)

TABLE 2: Load Loop Energy Balance Summary

ning. The facility will be run for a series of days using typical meteorological data for Madison, Wisconsin. Improvements are underway to permit comparisons of on/off and proportional flow control in the collector loop. The test facility will a valuable resource to compare alternative control strategies for active solar systems in a controlled laboratory environment where accurate and repeatable observations can be made. Our goal is to improve the utilization of solar energy through improved controls and control strategies.

REFERENCES

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[2] "Electronic Controller Development and Evaluation of Control Strategies," M. Wahlig and M. Warren. (LBL-8381) Sept. 1978. Proc. of 3rd

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[3] J. A. Duffie and W. A. Beckman, Solar Thermal Processes (New York; John Wily & Sons, 1974).

[4] Merle F. McBride, "Measurement of Residential Thermostat Dynamics for Predicting Transient Performance," ASHRAE, 85 (1979), PH-79-7A.

[5] P. J. Hughes and J. H. Morehouse, "A TRNSYS-Compatible, Standardize Load Model for Residential System Studies," Draft Report, May 1979, Science Applications, Inc.
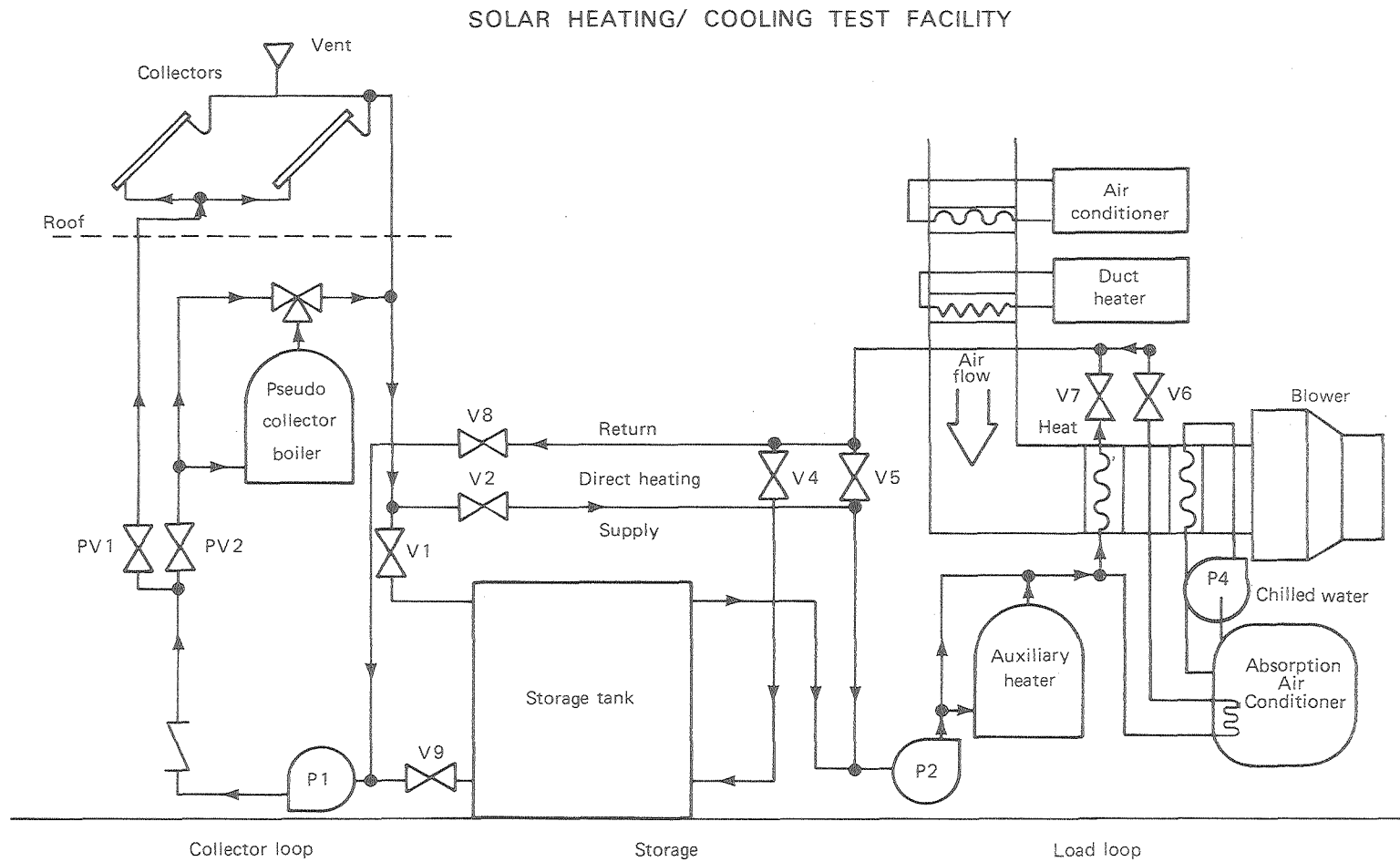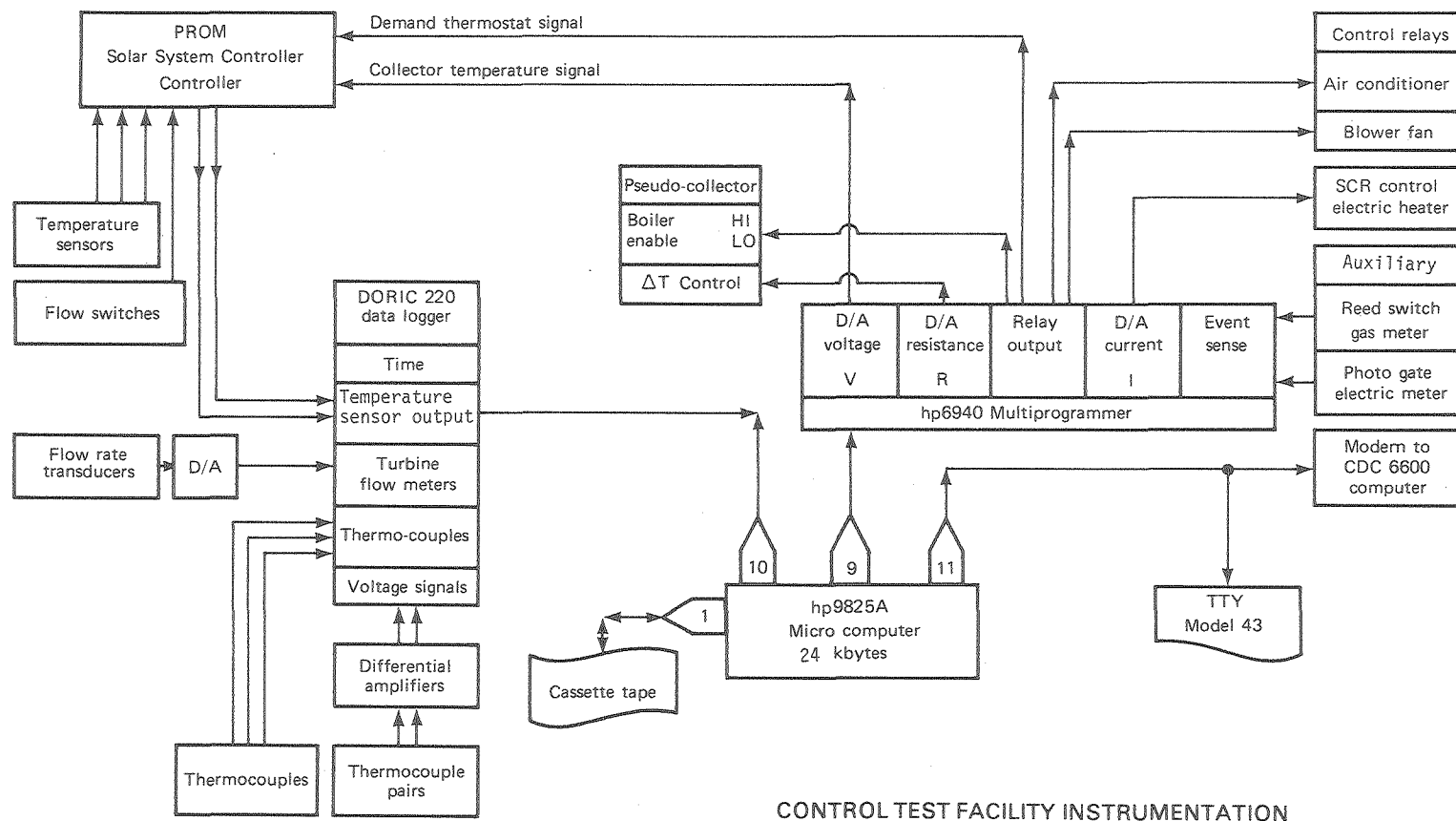
SOLAR HEATING/ COOLING TEST FACILITY

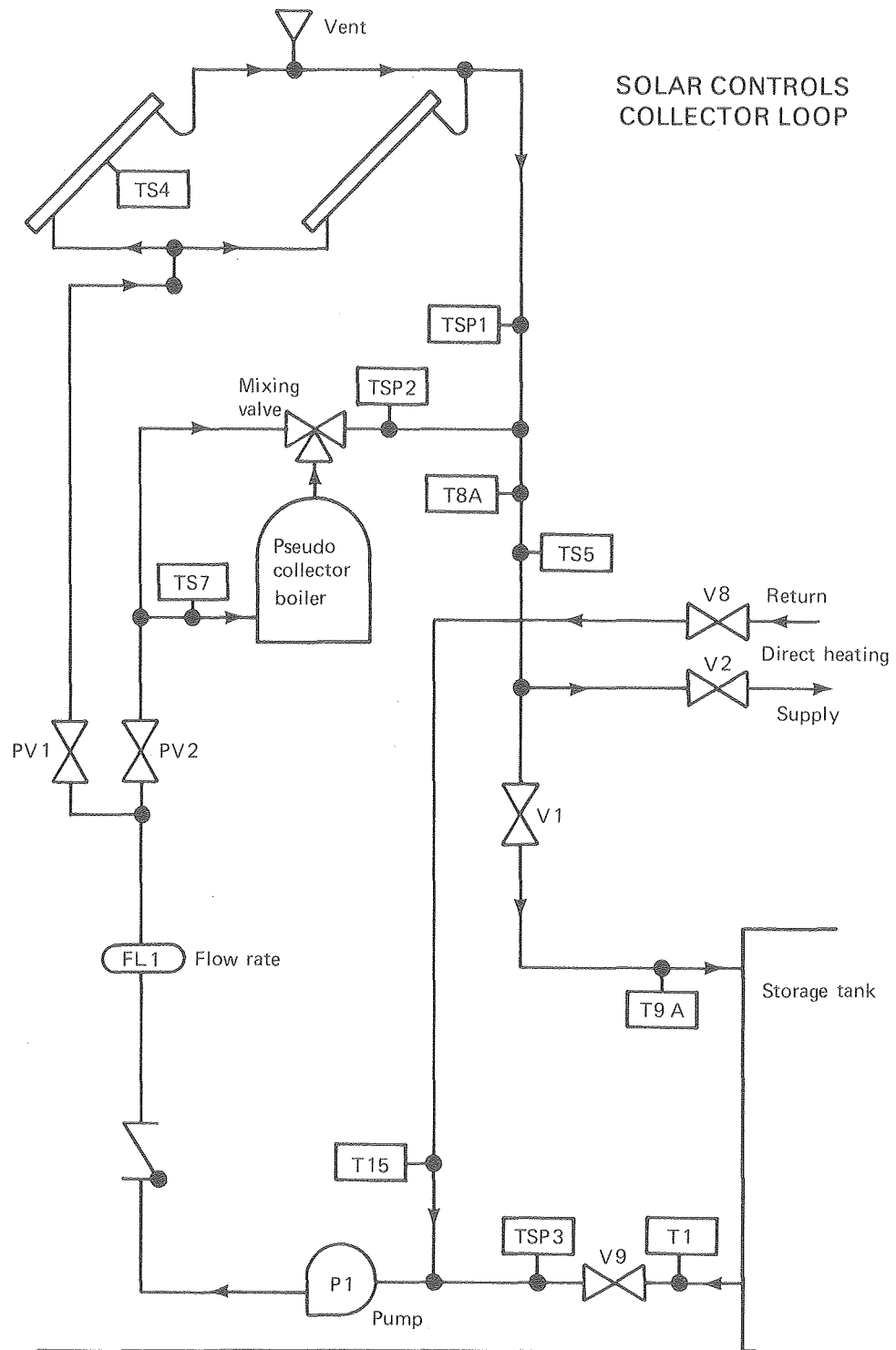Figure 1. Solar Controls Heating and Cooling Test Facility.
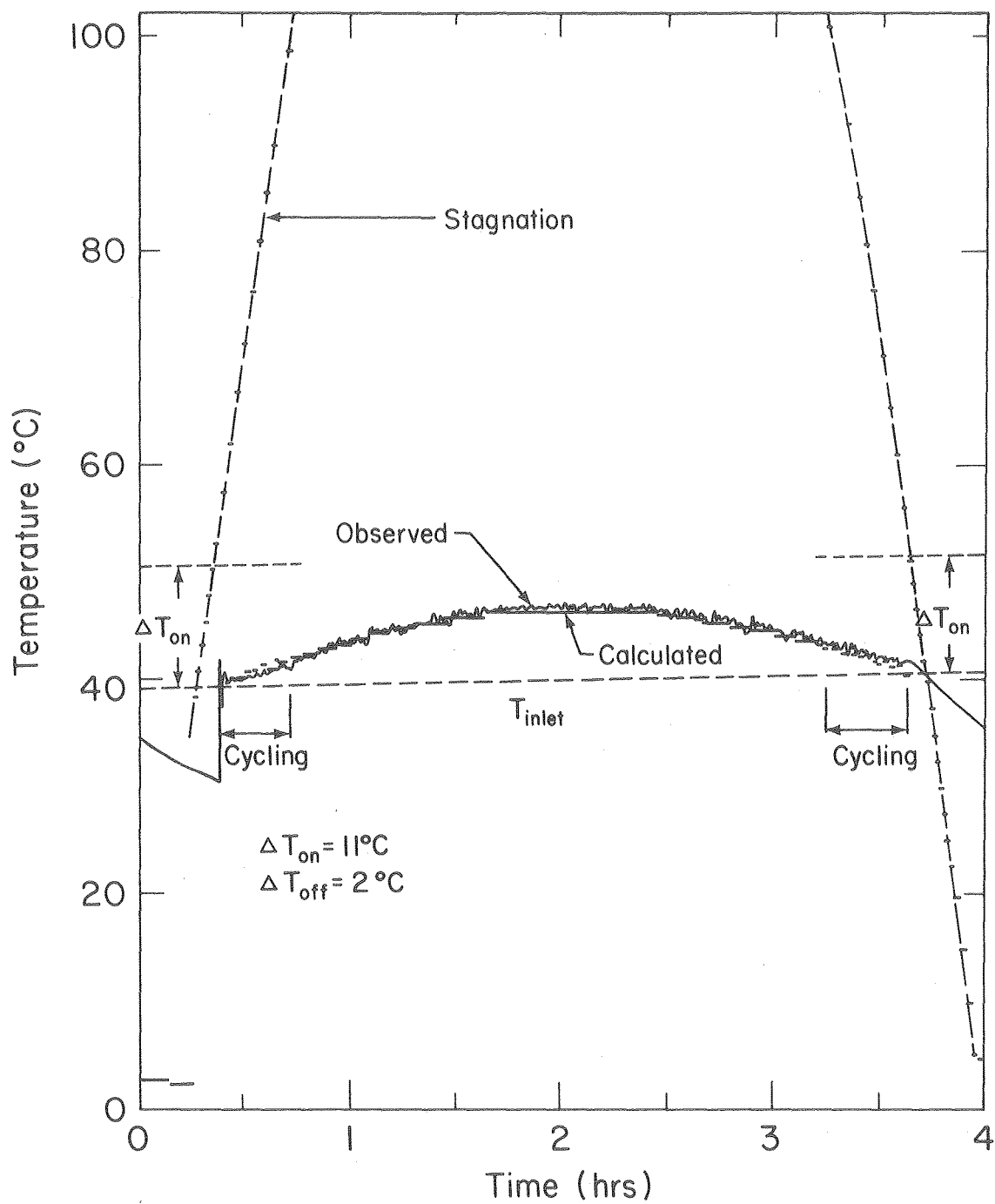
CONTROL TEST FACILITY INSTRUMENTATION

XBL 794-1149

Figure 2. Test Facility Instrumentation.

Figure 3. Solar Controls Facility Collector Loop showing pseudocollector boiler. The collector aray is not used and the collector input is simulated using the boiler with a mixing valve.

XBL 794-1152

Figure 4. Pseudocollector output. Calculated temperature (no flow), Calculated outlet temperature (flow), and Observed pseudocollector outlet temperature.

SOLAR CONTROLS-LOAD SIMULATOR

Air inlet

T50

Air conditioner

T55

Electric heater

T56

FL2

Air flow

T13A

V7

V6

Chiller

Blower

Heater

Air flow

TS6

V8

Return

Direct Heating

V4

V5

T57

T58

T59

V2

Supply

T12A

T10

TSI

P4

Storage tank

Auxiliary heater AUX

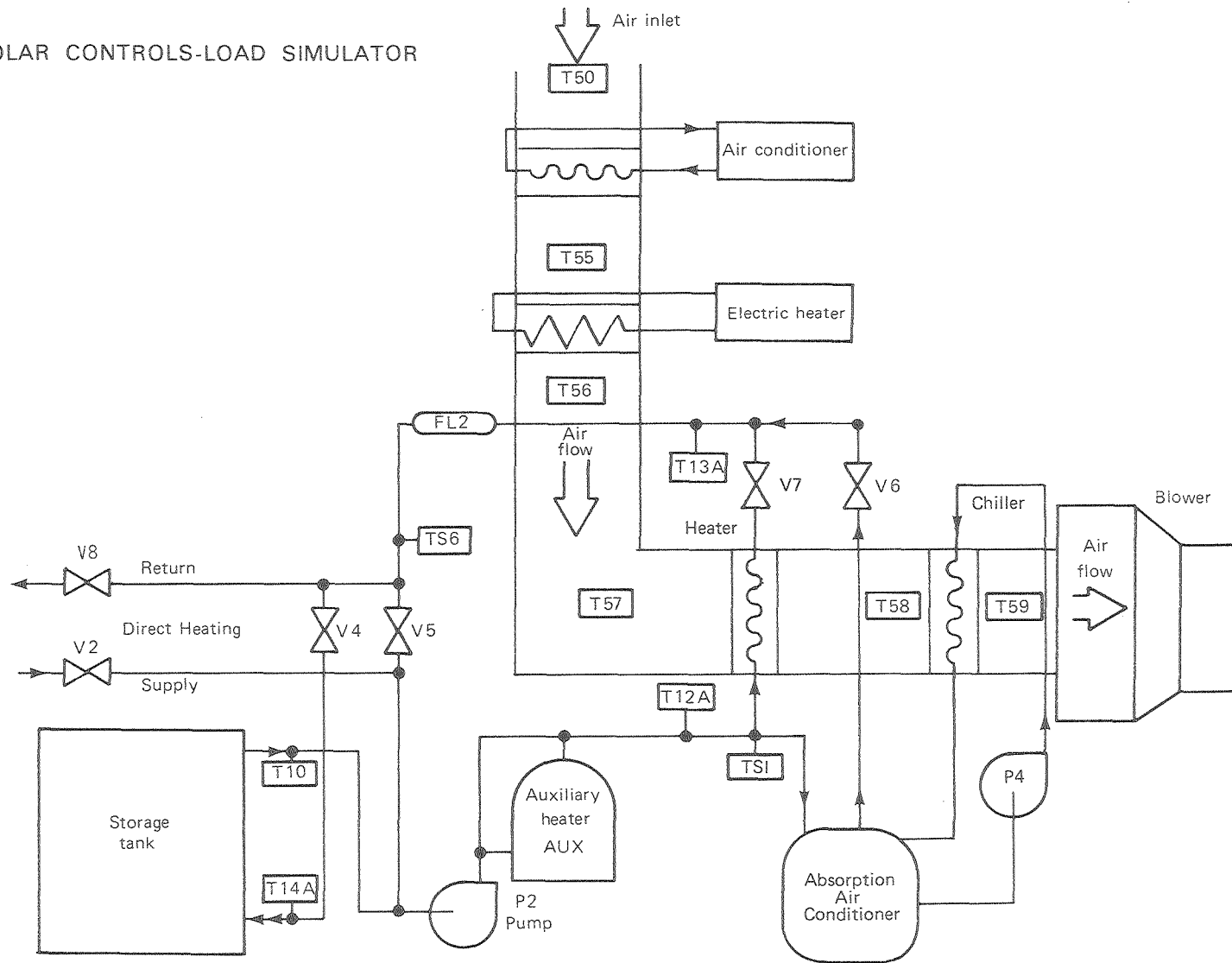Absorption Air Conditioner

T14A

P2 Pump

Figure 5. Solar Controls Facility Load Simulator showing load loop and air channel. The temperature of the inlet air measured by T57 is regulated to 20°C.

XBL794-1150